How do scientists think?

Or - at least - how do I, an experimental particle Physicist, think about science after 50 years of doing it?

Peter S. Cooper

Scientist Emeritus
Fermi National Accelerator Lab

Ask a Scientist
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Outline

This will be an undergraduate style seminar.

- I'm going to ask a lot of questions.

- I'm going to expect answers, and many questions from you.

This will be mostly by example. I'm not going to talk about how scientists think, I'm going to go through some scientific thinking trying to explain along the way.

- Introduction

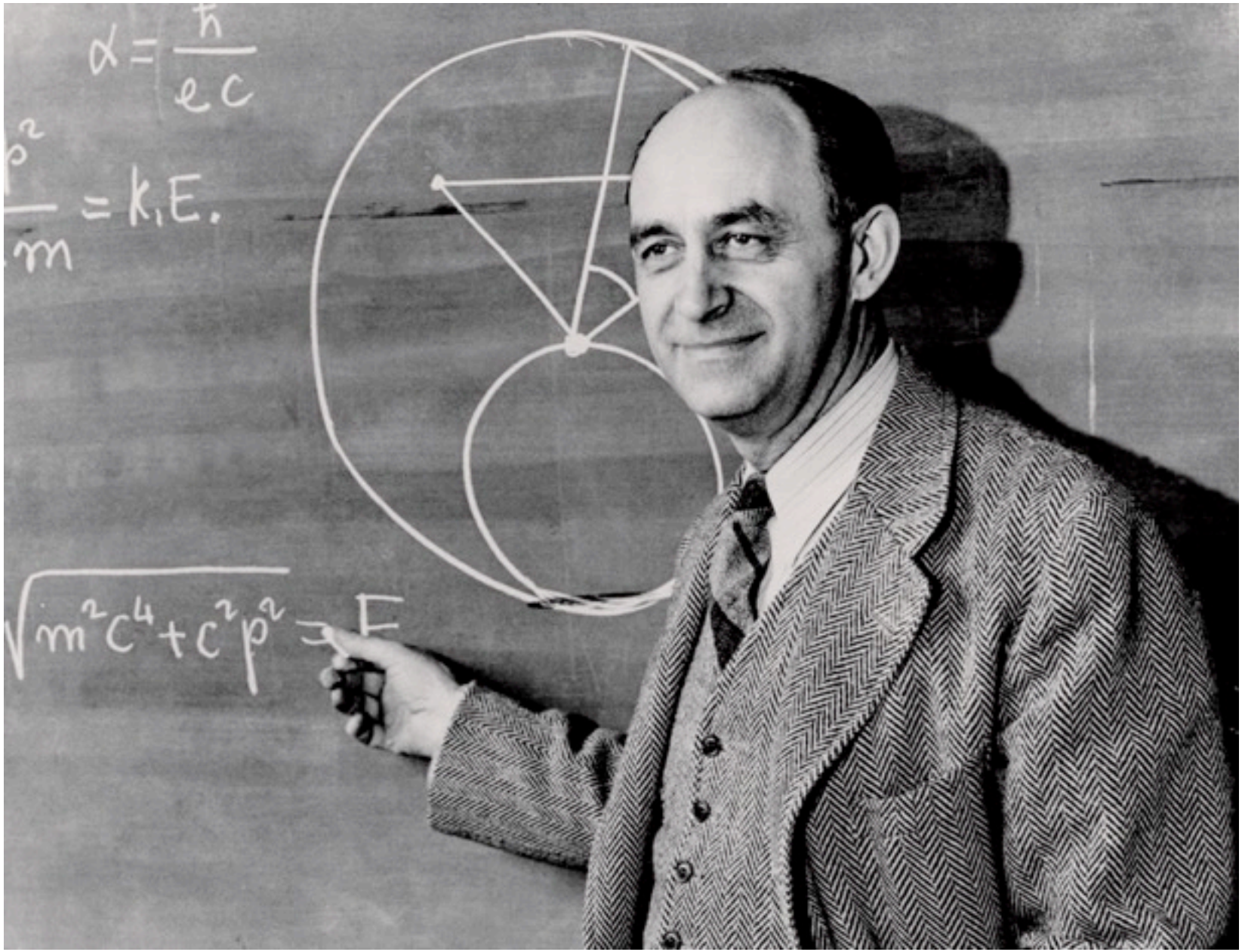
- Estimation - if it isn't quantitative it isn't Science

- Sociology - Who are scientists? How do they work together?

- Quotations - What do much better scientists have to say?

- Questions

Who is This? (equations?)

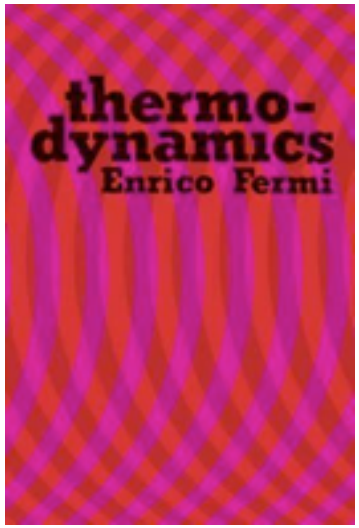


Enrico Fermi

- I just finished reading a biography of Fermi "The Pope of Physics" by Gino Segre and his wife Bettina Hoerlin: a good read. Fermi was given the moniker "the pope" by his colleagues for his infallible ability to estimate or predict the results of any physical experiment.

- In a famous tour-de-force he dropped strips of paper just as the blast wave from the Trinity test arrived, consulted an index card with some prior calculations, and correctly estimated the yield as 10 Ktons!

- Fermi was one of the greatest Physics teachers, ever:
  - His courses are still taught.
  - 6 of his 15 graduate students went on to win Nobel prizes. (yeah - he only took on the best students.)



Estimation

Fermi taught all his student estimation as a foundational skill required of a scientist.

- His classic problem was "How many piano tuners are there in Chicago?"
- Pianos and tuners having largely gone away. I learned this as "How many barbers are there in New Haven?"
- So - How many barbers are there in Naperville?

Rules

I want reasonable, but rational, estimates: 50% is fine.

Put the smart phones down. We're working with your intelligence not the internet's. Can you think quantitatively?

We're going to work on the whiteboard not in powerpoint

How many barbers in Naperville?

A blackboard calculation

What's wrong with this?

- Assumes equilibrium
- Doesn't scale (how many barbers at Fermilab?)
- Wouldn't asking about the fraction of the population who are barbers be a better question?

What did we just do?

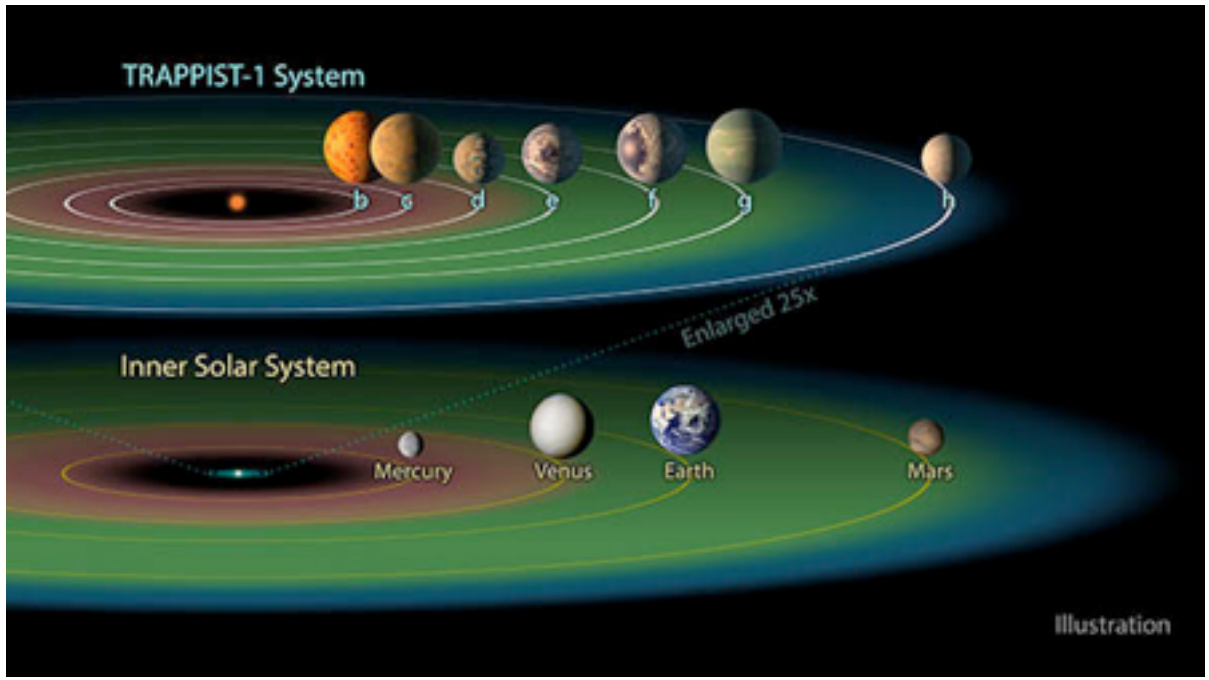
- Pose a quantitative physical question.
- Build a model for how to answer it.
- Estimate the parameters of the model from the world around us.
- Get an answer that is sensible and reasonable.
- Ask what we did wrong, how can we do better, and most importantly, have we asked a sensible question?
- Repeat as required.

This is usually known as the scientific method.

A recent discovery

Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1

Nature **542** 456-460 (2017) http://dx.doi.org/10.1038/nature21360 One aim of modern astronomy is to detect temperate, Earth-like exoplanets that are well suited for atmospheric characterization. Recently, three Earth-sized planets were detected that transit (that is, pass in front of) a star with a mass just eight per cent that of the Sun, located 12 parsecs away[1]. The transiting configuration of these planets, combined with the Jupiter-like size of their host star—named TRAPPIST-1—makes possible in-depth studies of their atmospheric properties with present-day and future astronomical facilities[1, 2, 3]. Here we report the results of a photometric monitoring campaign of that star from the ground and space. Our observations reveal that at least seven planets with sizes and masses similar to those of Earth revolve around TRAPPIST-1. The six inner planets form a near-resonant chain, such that their orbital periods (1.51, 2.42, 4.04, 6.06, 9.1 and 12.35 days) are near-ratios of small integers. This architecture suggests that the planets formed farther from the star and migrated inwards[4, 5]. Moreover, the seven planets have equilibrium temperatures low enough to make possible the presence of liquid water on their surfaces[6, 7, 8].



A Physics problem

How can you predict the surface temperature of a planet?

First a practical example

What is the predicted surface temperature of the Earth?

If we can build a model for this, and check that it gets the right answer, then we can apply it to other similar systems.

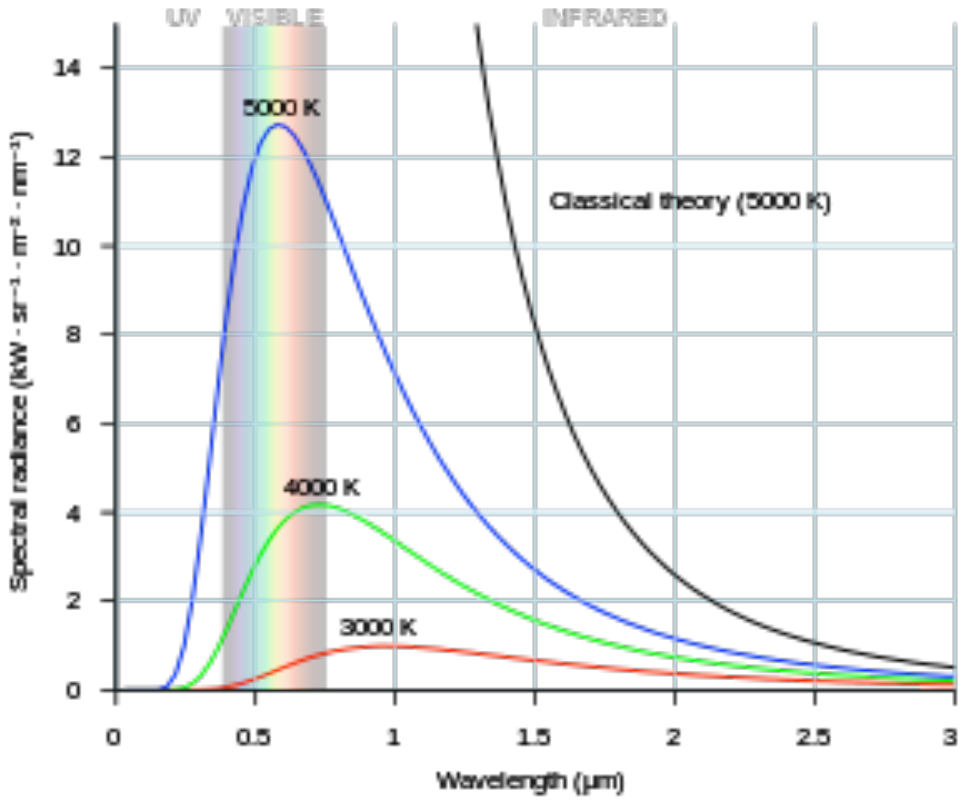
- Where does Earth's heat come from?
- How does it get here?
- How does it leave?
- What's the Physics of this?

Blackbody radiation primer

- A blackbody is an object which absorbs all radiation falling upon it.

- Absorbing radiation increases its internal (thermal) energy; e.g. its temperature.

- It must lose energy at the same rate to reach thermal equilibrium at a finite temperature. This is blackbody radiation.



- The total power per unit surface area of blackbody radiation is

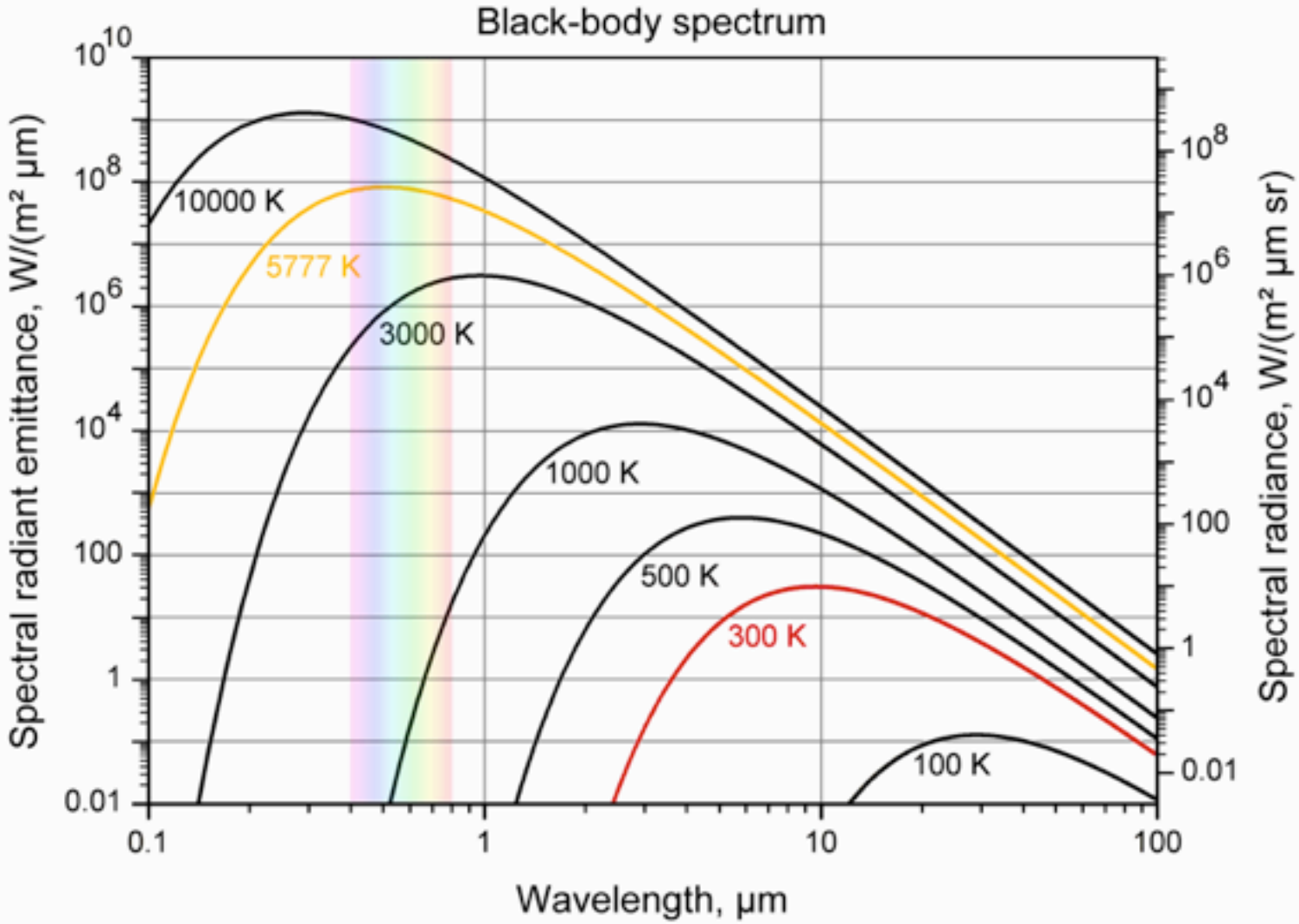
$$P/A\ [\text{watts/m}^2] = \sigma T^4$$

σ is the Stefan Boltzmann constant
T [K] is the absolute temperature

Science from a graph

- The spectrum is universal depending only on temperature.

Cherry red hot iron (1000K), coming out of a blacksmith's forge, is emitting blackbody radiation. The color and the temperature are related.



Surface temperature of the earth

What have we left out?

Does this look like a 300K blackbody to you? It can't your eyes, or the film, don't see 300K radiation. Glass (lens) is opaque to 300K (10μm) and transparent to visible (0.5μm) light. This is why a green house works.

30% of the sunlight which hits the earth is reflected, not absorbed and re-emitted as blackbody radiation. This is albedo:

$[1-a]^{1/4} = 0.91 \quad 280K \rightarrow 260K$

What have we left out? (2)

The earth's mean surface temperature is about 288K (15C)
Why +30K (=30C) hotter?

Water (H_2O), Carbon Dioxide (CO_2), Methane (CH_4) and other atmospheric gasses have optical properties like glass; they let visible radiation from the sun in but absorb infrared (300K) radiation and reradiate it back down. This is the green house effect.

Venus (96% CO_2 atmosphere now) is 735K when the albedo blackbody calculation predicts 310K. How it got that way is a longer story.

"Climate change" is political The optical absorption properties of gases are not: they're measured.

The scientific viewpoint

Nature doesn't negotiate. She does what she does.

Our role is to try to learn what she does - by looking. The imperfections in our knowledge and understanding are our problems, not Nature's.

Opinions and beliefs are very important to us humans. Nature neither knows nor cares. She does what she does. To the best of our ability to tell she does it the same everywhere and everywhen.

There are other ways to look at the world than the scientific viewpoint. They are different. What you see depends upon where you stand and how you look.

Plato taught us that there may be "Truth" but we don't get to know it. Science just tries to make sense of what we see.

Scientific training

I just took you through one undergraduate level homework problem.

Do ~1000 more of these, by yourself, and get most of them right, and you can have a Bachelors degree in Physics.

That training will give you to vocabulary and the tools of the science

The scientists, living and dead, you work with and study will show you how to think scientifically, mostly by example.

The best scientists are the clearest thinkers. The exceptional (e.g. Fermi) can also communicate extremely clearly. This, apparently, can be taught at some level. Fermi training 5 students in a decade at the University of Chicago who went on to win Nobel Prizes is not a likely statistical fluctuation (luck).

Other Earth Energy questions

What are the supply and demand rates for Carbon?

- How did most of that fossil Carbon get down there?
- How long did that take?
- How long will take for us to extract most of it?

- What is the ratio?
- Where did the energy come from?

Total Solar power 174,000 TW
Other sources (radioactive decay 20TW, formation heat 30TW)

- Where did this energy come from?

“Energy is neither created nor destroyed, just changed in form.”

Scientists are (diverse) people

E761 (1990) one of my experiments

- **By training**
  - 17 Physicists - 6 graduate students,
    now 3 Physics professors
    3 Senior Engineers
  - 6 Engineers
  - 1 Technician

- **By nationality**
  - 9 Russians
  - 2 Chinese
  - 5 Brazilians
  - 1 Mexican
  - 1 Brit
  - 6 Americans (one still with his hair)

- **By Gender**
  5 / 24 women - but no Americans

это нормально (this is normal)

Sociology of Scientists

- Collaborations of scientists operate like families

(all of mine have been and are, but that says something about me)

- The actual doing of science is anything but scientific.
- There is argument, disagreement, hurt feelings, and more than a little love. Families!
- The challenge is to learn about nature, and to make the experiment work, correctly, NOW!

- The differences which separate us are small compared to the science which binds us. Governments and bureaucracies (all of them) are obstacles to be overcome to get the experiment done.

- Why is the "World Wide Web" so open? Recall it was invented by, and for, us.

- My undergraduate thesis advisor observed that if physicists could just get fed they'd do Physics for nothing. He was right.

What some better scientists think about science

- **Isaac Newton**

"I was like a boy playing on the sea-shore, and diverting myself now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

- **Enrico Fermi**

  “It is no good to try to stop knowledge from going forward. Ignorance is never better than knowledge.”

  “If I could remember the names of all these particles, I'd be a botanist.”

- **Luiz Alvarez**

  “There is no democracy in physics. We can't say that some second-rate guy has as much right to an opinion as Fermi.”

- **Isidor Rabi**

(My professional grand-father: e.g. my thesis advisor's thesis advisor
My grandson and grand daughter together now lead a Fermilab experiment.)

"I think physicists are the Peter Pans of the human race. They never grow up and they keep their curiosity."

"My mother made me a scientist without ever intending to. Every other Jewish mother in Brooklyn would ask her child after school, So? Did you learn anything today? But not my mother. Izzy, she would say, did you ask a good question today? That difference - asking good questions - made me become a scientist."

So who has some good questions?